INNOVATIVE QUANTUM TECHNOLOGIES FOR MICROGRAVITY FUNDAMENTAL PHYSICS AND BIOLOGICAL RESEARCH

Isabella Kierk

September, 2001

ABSTRACT

The many advanced technology requirements dictated by the demanding low-Earth orbit research environment can only be satisfied through the adaptation of innovative methods and technologies. The fundamental physics research program in microgravity sponsors research that explores the physics governing matter, space, and time and that seeks to discover and understand the organizing principles of nature, including the emergence of complex structures. The fundamental physics research program currently supports research in four areas: gravitational and relativistic physics, laser cooling and atomic physics, low temperature and condensed matter physics, and biological physics. The microgravity fundamental physics is one of the science disciplines within the new NASA Office of Biological and Physical Sciences Research, where quantum technology plays a major role. Quantum technology, based on controlled manipulation of fundamentally quantum processes of atoms, molecules, or soft matter, enables novel and significantly extended capabilities. This paper presents a new technology program, within the fundamental physics research program, focusing on four quantum technology areas: quantum atomics, quantum optics, space superconductivity and quantum sensor technology, and quantum fluid based sensor and modeling technology. Specific innovative technology development approaches within these areas as well as a potential for international collaborations will also be discussed.

Fundamental Physics Overview

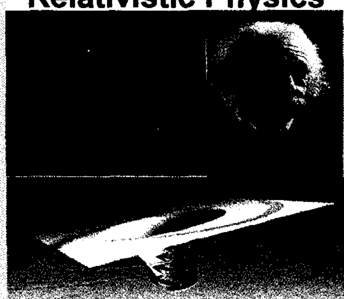
Jet Propulsion Laboratory
California Institute of Technology

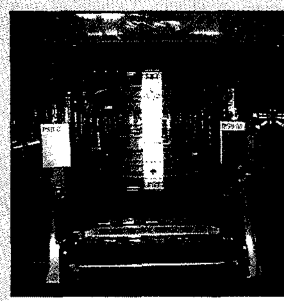
- ***Two long-term Quests that motivate our research***
- ***Five research areas pursued to seek answers to our Quests***

Quest One

To Discover and Explore Fundamental Physical Laws Governing Matter, Space, and Time

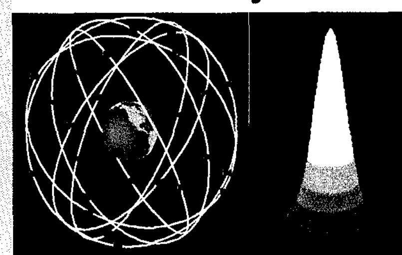
Gravitational and Relativistic Physics





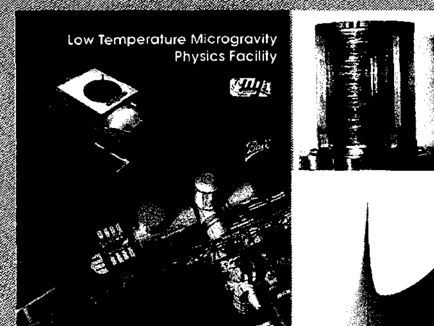
High-Energy Physics

Laser Cooling and Atomic Physics



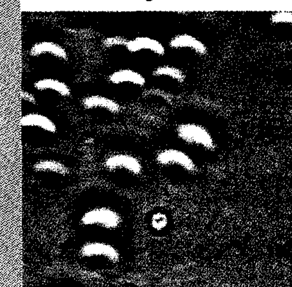
Quest Two

To Discover and Understand Organizing Principles of Nature from which Structure and Complexity Emerge



Low Temperature and Condensed Matter Physics

Biological Physics

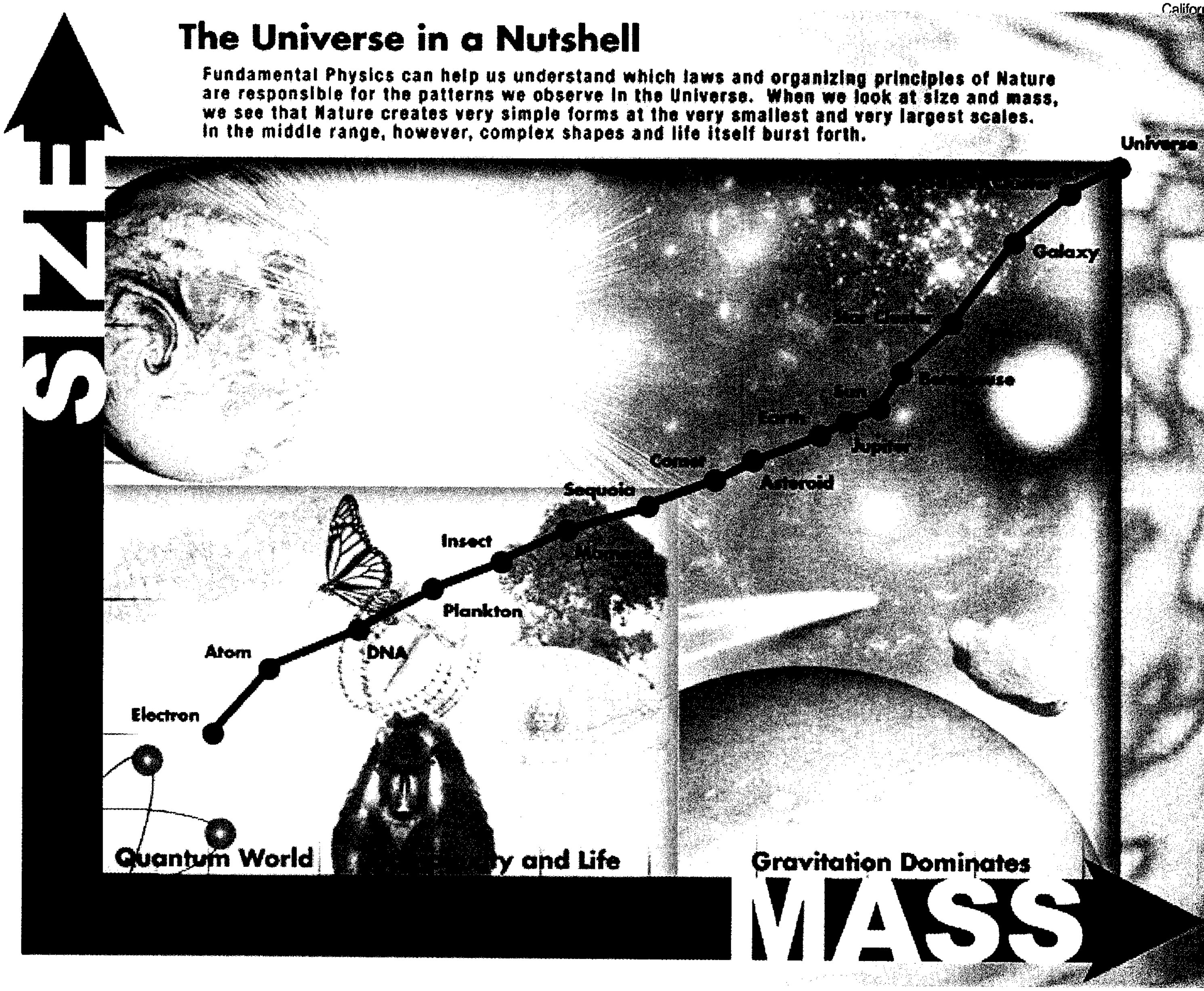


Our Benefits:

Fulfill the Innate Human Desire to Understand our Place in the Universe

Build the Foundation for Tomorrow's Breakthrough Technologies

The Universe in a Nutshell



Low Temperature and Condensed Matter Physics

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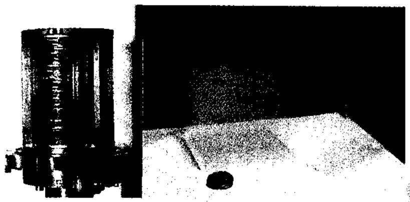
Using the Space Environment to Investigate:

Confinement and Boundary Effects

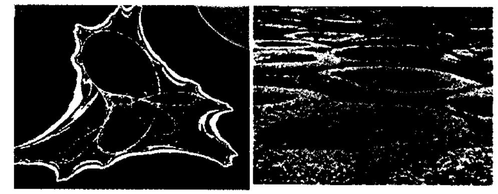


How boundaries, size, and dimensionality affect properties near a phase transition

Non-equilibrium Phase Transitions

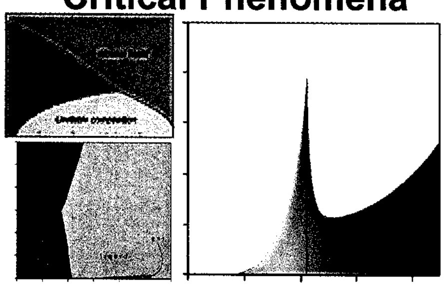
How applied forces affect the nature of a phase transition

Fractal Structures and Pattern Formation



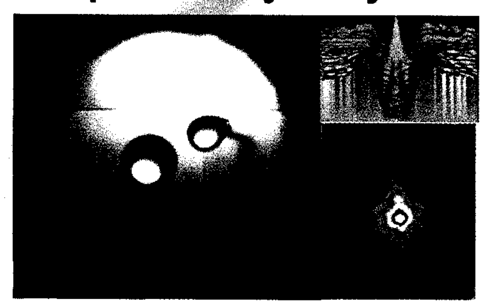
How the breaking of symmetry is used by nature to form patterns

Critical Phenomena



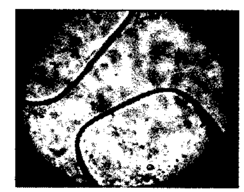
If properties near continuous phase transitions are universal and what scaling laws exists.

Superfluid Hydrodynamics



How fluid motion and nucleation of vortices in isolated drops of superfluid helium occurs

Quantum Solids



How nucleation of non-equilibrium solid phases, and rapid transformation to other solid phases occurs

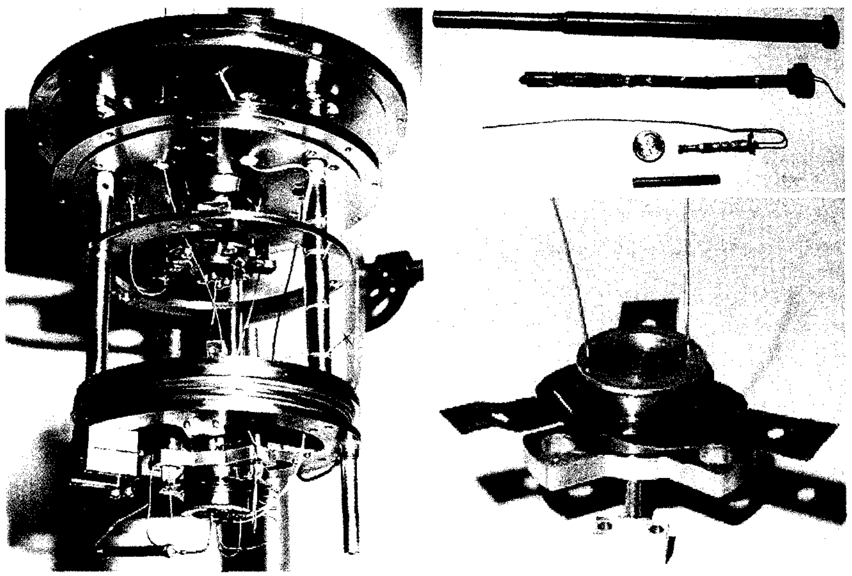
2000 2015 Future

Low Temperature Microgravity Physics Facility (LTMPF)

- ISS cryogenic facility
  - Cold (≈ 2 K) volume for experiments
  - 5 months lifetime
  - Microgravity environment
  - Environments monitored
  - Multiple-experiments per flight
- Launched on the Space Shuttle
- Attached to the Japanese External Module Exposed Facility
- First launch planned November 2005
  - 2 instruments conducting 4 experiments
- Brought to Earth following helium depletion to refurbish with new instruments for next flight
  - 22 months between launches

Critical Dynamics in Microgravity Experiment (DYNAMX) (R. Duncan ISS 4/05)

MOTIVATION: **Dynamic properties near second order phase transitions have wide scientific and technological application but are relatively poorly understood.**



Science Objectives

To examine dynamic properties of the superfluid transition under non-equilibrium conditions with sub-nanoKelvin temperature resolution

- **Measure the thermal conductivity in the linear and nonlinear regions, and compare to theories.**
- **Measure temperature profile and its scaling behavior near the interface.**
- **Improve the determination of the transition temperature suppression by a factor of 10.**
- **Search for the hysteresis with a factor of 100 improvement in sensitivity.**

Technology

- **Ultra-compact or thermal component-isolated high resolution thermometer to minimize cosmic ray impacts**
- **Pico-watts thermal control.**
- **Composite thermal conductivity cell with ultra-thin sensor probes penetrating the thin side-wall of the thermal conductivity cell.**

Mission Description

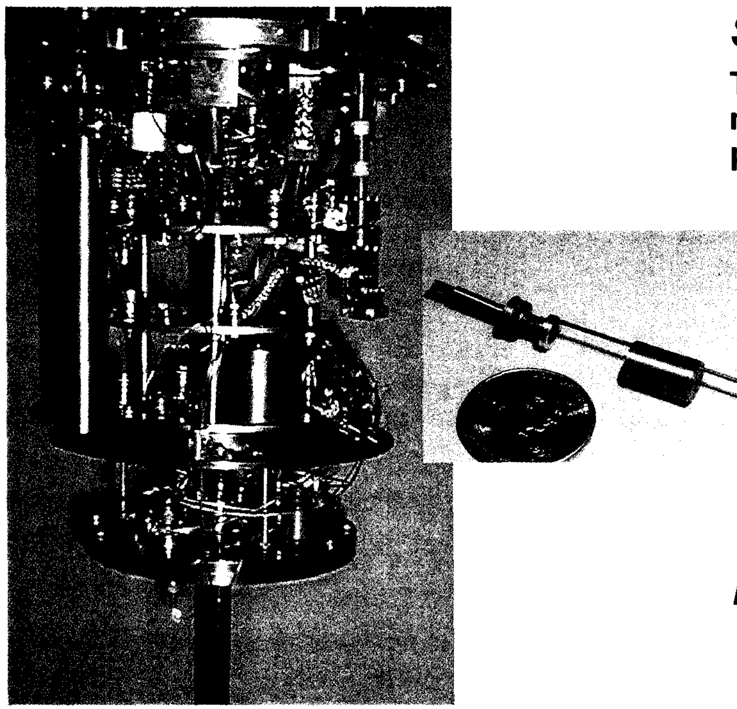
- **Selected for flight on the M1 mission on LTMPF on the International Space Station.**
- **Three months data acquisition.**

Measurement Strategy

- **Use multiple high resolution thermometers attached to the thermal conductivity cell side-wall.**
- **Use heat current-biased thermal control.**

Microgravity Scaling Theory Experiment (MISTE) (M. Barmatz ISS 4/05)

MOTIVATION: **To perform the most accurate test of the scaling law predictions in a simple testbed system to improve our understanding of the range of validity of scaling theory**



Science Objectives

To measure critical exponents near ^{3}He critical point in microgravity; provide the most accurate test of scaling law predictions.

- **Perform precision measurements of the specific heat at constant volume C_V, and of the isothermal compressibility k_T, near the liquid-gas critical point of ^{3}He in a microgravity environment**
- **Improve the precision of the critical exponents α, γ, δ from these measurements along the critical isochore and isotherm**
- **Test the scaling law relation between these exponents and the theoretical predictions for the measured critical exponents.**

Mission Description

- **Selected for flight on the M1 mission on LTMPF on the International Space Station.**
- **Three months data acquisition.**

Measurement Strategy

- **Develop high resolution pressure, density, and temperature sensors to determine critical point parameters (P_c, ρ_c, and T_c) accurately and to perform P, ρ, T measurements in the critical region.**

Technology

- **Miniature $GdCl_3$ high-resolution thermometer operating near 3.3K**
- **Miniature cryogenic valve**
- **High-resolution density and pressure sensors**

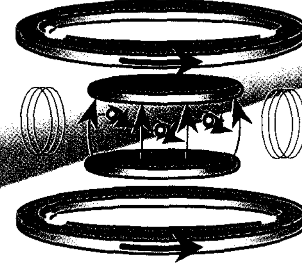
Laser Cooling and Atomic Physics

Using the Space Environment to Investigate:

Laser-Cooled Atomic Clock

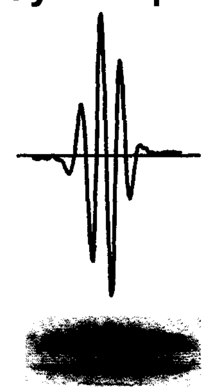
If all clocks keep the same time or if our description of nature's forces is incomplete.

Electron-Dipole Moment



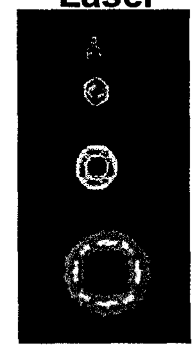
If the electron has a dipole moment and if the standard model of particles and fields has to be modified.

Matter Wave Gyroscope



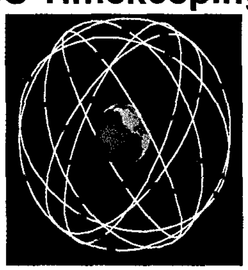
If space can be used to establish stringent bounds on fundamental laws and forces of nature

Atom Laser



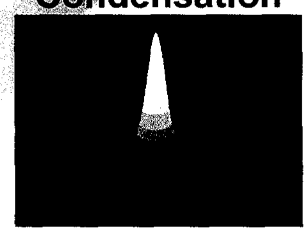
If we can build improved atom lasers in microgravity.

ISS Timekeeping



If a NASA clock on the ISS can provide improved timing for all scientists

Bose-Einstein Condensation



If current theories of atomic interactions are correct

2000 2015 Future

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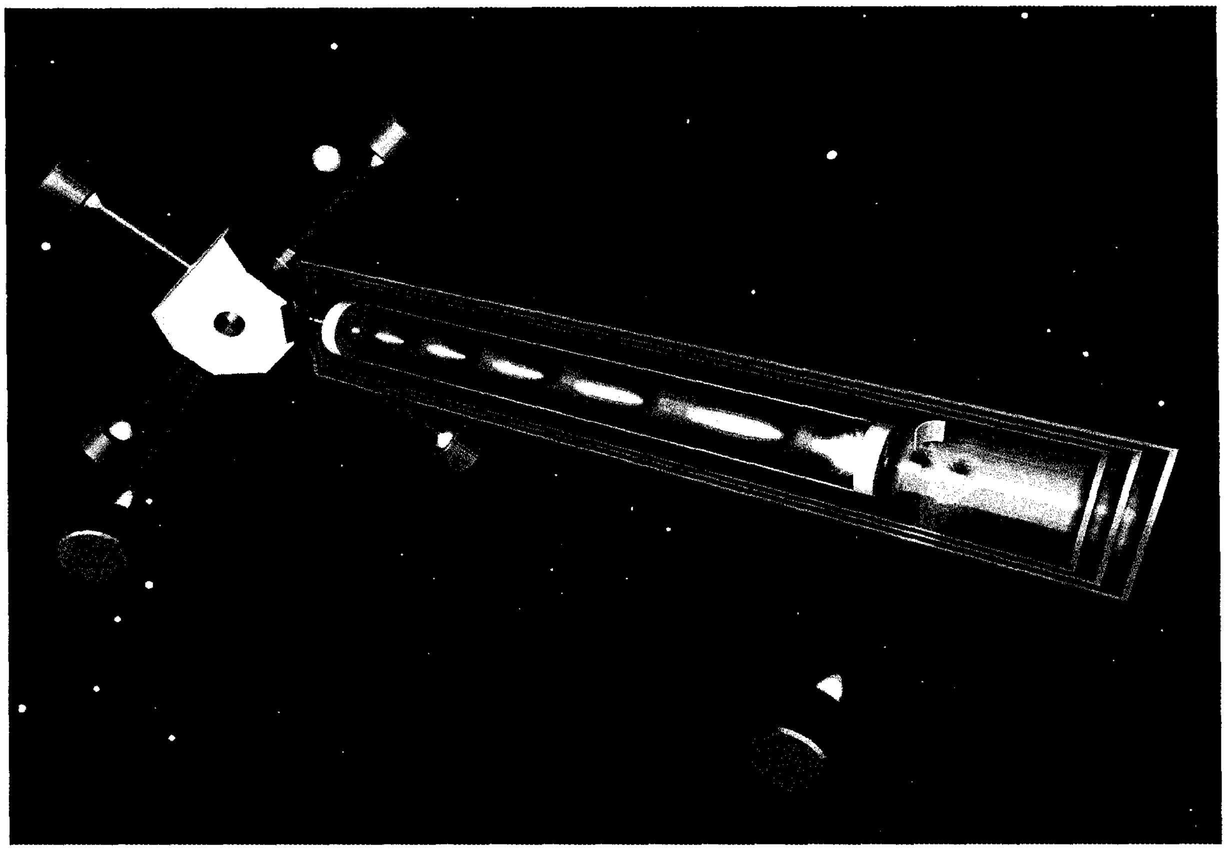
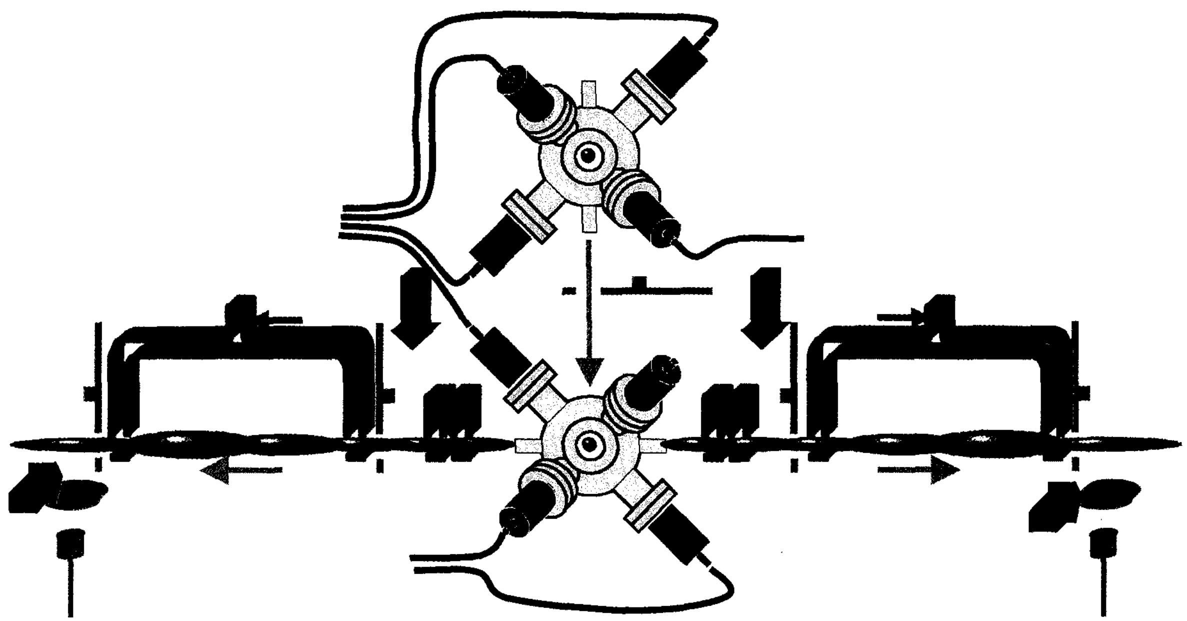
Primary Atomic Reference Clock in Space (PARCS)



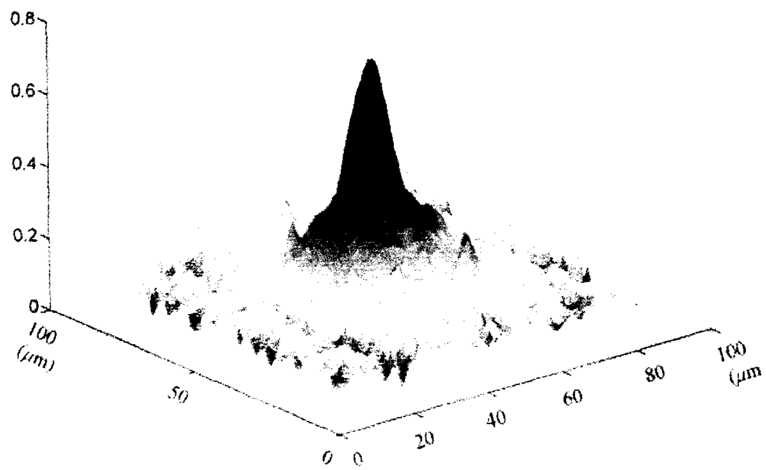
- August 2005 planned launch
- Takes advantage of the free-fall environment to develop the world's most accurate clock.
    - Improves the realization of the second to 10^{-16} accuracy.
- Performs tests of general relativity by comparing its clock frequency to different units.
- Makes available improved time coordination for clocks on Earth

Rubidium Atomic Clock Experiment (RACE) (K. Gibble ISS)



1. Advance atomic clock science and techniques to enable measurements with accuracy of 1 part in 10^{17}.
2. Significantly improve the classic clock tests of general relativity.
3. Distribute the highest accuracy time and frequency from the ISS.

Bose-Einstein Condensation Experiment (BEC)



Science Objectives

- To demonstrate Bose-Einstein condensation of Rb in space
- To perform measurements of the temperature and density and greatly extend the accessible parameter space
- To demonstrate matter wave interference with binary mixture condensate

Mission Description

- Rack mounted aboard the International Space Station or as attached payload
- Space MOT
- Magnetic Trap for Space

Technology

- Magneto Optical Trap (MOT)
- Diode Lasers suitable for Rb
- Ultra-high vacuum
- Magnetic Trap
- Optical components

Measurement Strategy

- Compare with the ground based condensate
- Demonstrate lowest temperature

Gravitational and Relativistic Physics

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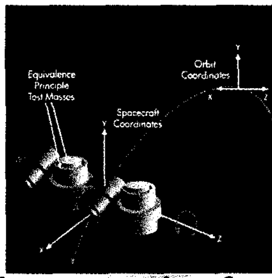
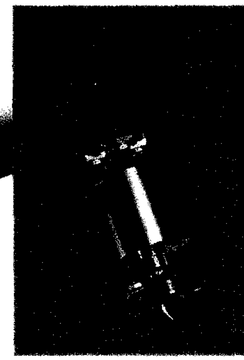
Using the Space Environment to Investigate:

Equivalence Principle and Long Range Fields



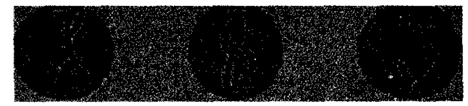
If there are other forces beyond the four known. STEP will achieve a million-fold improvement. NASA Codes U & S, ESA

Advanced Clocks



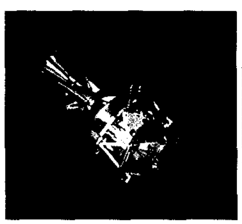
If all clocks keep the same time or if our description of nature's forces is incomplete.

Clues to Unification



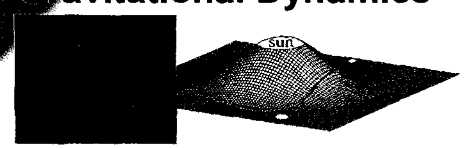
If our current theories of gravitation can be modified to unify with quantum physics

Frame Dragging



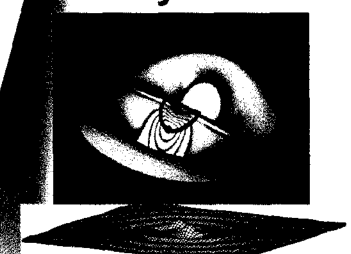
If the rotating Earth drags Space time as predicted by Einstein's theory. GP-B will measure this effect directly (Code S)

Gravitational Dynamics



If our understanding of physics holds true in the 'strong gravity environment' near black holes. (Code S)

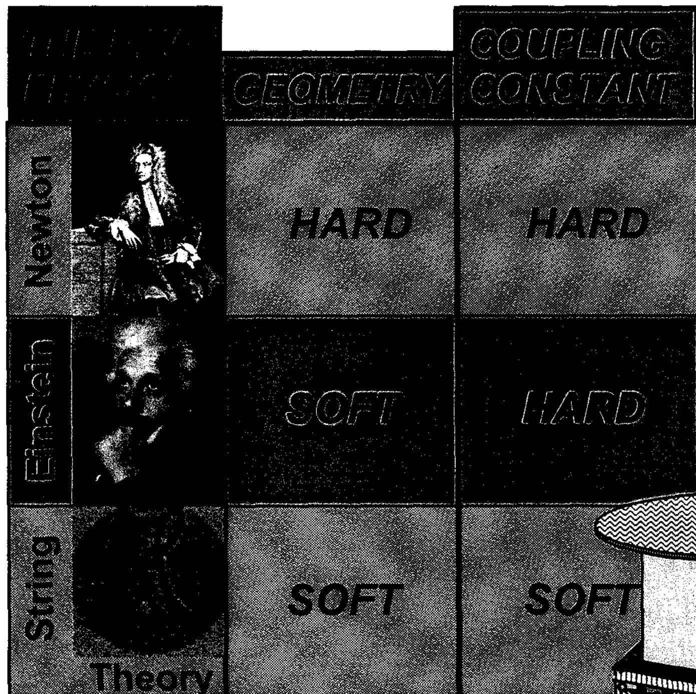
Gravity Waves

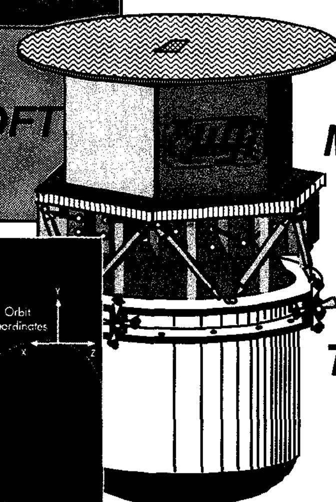


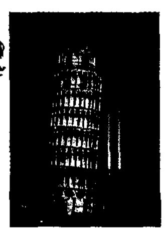
If our understanding of gravity waves is consistent with reality. (Code S)

2000 2015 Future

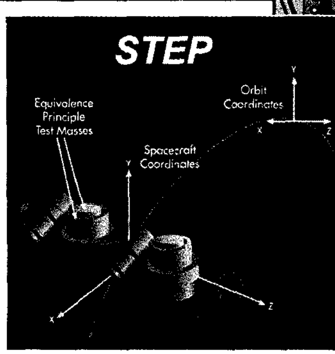
Satellite Test of the Equivalence Principle (STEP) (F. Everritt TBD launch)







Galileo Galilei



Science Objectives

- To verify the validity of one of the fundamental assumptions underlying Einstein's general theory of relativity -- the equivalence of inertial and gravitational mass, to a precision of 10^{-18}.
- To discover or rule out the existence of weakly coupled long-range forces

Mission Description

- Drag free spacecraft launched by LMLV-1 vehicle
- 400 kilometer sun-synchronous, polar orbit
- Six to eight months mission duration

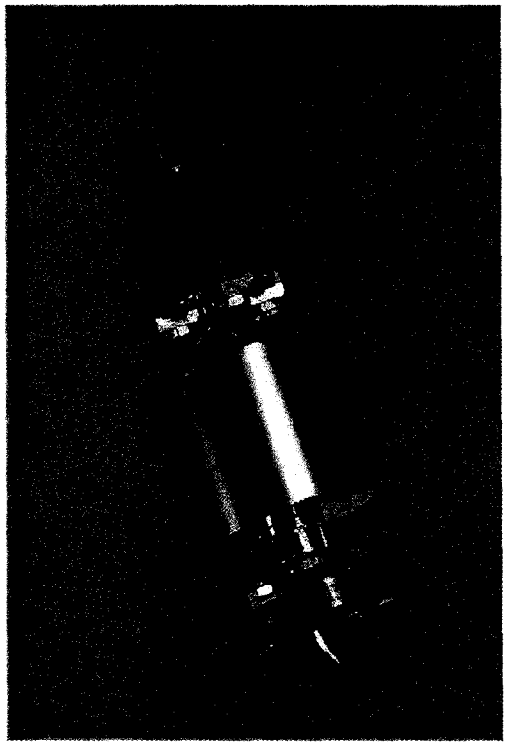
Measurement Strategy

- Measure relative positions of finely machined cylindrical test masses inside a low-temperature dewar using SQUID technology

Technology

- Differential accelerometer with noise < 10^{-15} g over 1,000 seconds
- Charge control system for test masses
- Gravity gradient control (helium tide)
- Drag-free satellite and micronewton thruster

SUperconducting Microwave Oscillator (SUMO) (J. Lipa ISS 2007)



Science Objectives:

- Compare a microwave cavity frequency with that of an atomic clock as a function of position and gravitational potential.
- Measure frequency differences to 1 part in 10^{17}.
- Provide a low phase noise signal capable of being slaved to an atomic clock.
- Longer term, perform a precision red-shift experiment using two microwave oscillators on different vehicles.

Mission Description:

- Candidate experiment for M2 mission on LTMPF on the International Space Station.
- Data acquisition: three to six months.

Technology:

- Ultra-high stability superconducting microwave oscillator.
- Low noise phase-locked loops.
- Operation at 1.2K.

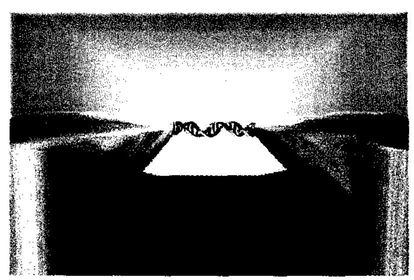
Measurement Strategy:

- Compare microwave frequencies to the micro-hertz level as a function of orbital position.

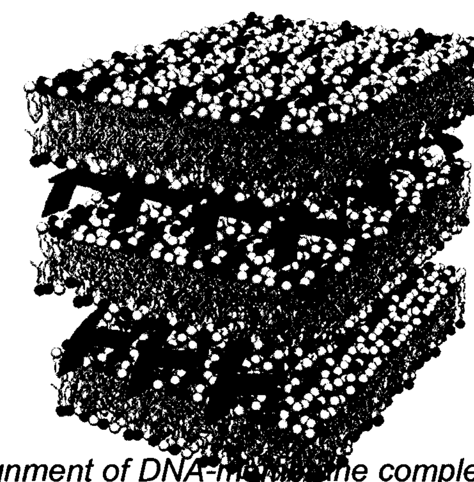
- *This year, at the request of the NASA Administrator and Associate Administrator for Life and Microgravity Sciences and Applications, a new subdiscipline, "Biological Physics," has been added*
  - *Definition of the sub-discipline is taken from American Physical Society*
  - *Specific content of discipline as implemented at JPL will be determined by what is proposed and selected.*
- *Promising areas of research will apply techniques of physics to the understanding of biological entities*
- *Seven ground investigations selected from 2000 NRA*

X-ray crystallography image of a complete ribosome (***Science***, 24 September 1999)

DNA shown to be a semiconductor.
DNA electronics now feasible



Nature, 10 February 2000



*Perfect alignment of DNA-m[illegible]e complex can serve as nano-fabrication template (**Applied Physics Letters**, 5 October 1998)*

- ***QUANTUM TECHNOLOGY FOR MICROGRAVITY AND BIOLOGICAL RESEARCH***
  - Quantum technology is based on controlled manipulation of fundamentally quantum processes of atoms, molecules, or soft matter to enable novel and significantly extended capabilities. It plays a major role in fundamental physics since it supports all sub-disciplines.
  - Motivation for developing quantum technology - a breakthrough approach to develop sensors:
    - *with significantly higher resolution/sensitivity than conventional technology*
    - *suitable for future micro-spacecraft*
    - *with capability to support NASA's robotic, and manned flight missions*
    - *significantly increasing science return*
  - Quantum technology exploits quantum coherence, quantum interference, quantum entanglement and quantum nonlocality to achieve the aim of greatly improved capabilities.
  - *There are four quantum technology sub-areas described in this theme area:*
    - *Quantum atomics,*
    - *Quantum optics,*
    - *Space superconductivity and quantum sensor technology,*
    - *Quantum fluid based sensor and modeling technology.*

- *QUANTUM TECHNOLOGY FOR MICROGRAVITY AND BIOLOGICAL RESEARCH (JPL)*
  - ***Quantum atomics*** will exploit coherent matter waves to realize never before possible capabilities for the development of novel and ultra-sensitive inertial sensors.
    - *Extremely sensitive gravity gradiometers to test the fundamental laws of physics, as well as allow sub-surface mapping of the earth and planetary structures and resources.*
    - *Coherent matter waves of Bose-Einstein Condensation, atom lasers, promise to find as many diverse applications as the conventional light laser*
  - ***Quantum optics****,* a field concerned with the coherence properties of light and its influence on interaction of light with matter has already led to advances in a number of familiar fields, such as coherent spectroscopy.
    - *A major promise of quantum optics is the creation of new sensors for biological and pre-biotic molecular research which would enable the study of biological entities at single molecular level to provide the needed understanding to link biology with the underlying laws of physics.*
    - *They also lead to the needed capability to detect life beyond earth, as well as the presence of harmful molecules in space habitats.*

- *QUANTUM TECHNOLOGY FOR MICROGRAVITY AND BIOLOGICAL RESEARCH (JPL)*
  - ***Space Superconductivity and Quantum Sensor Technology***
    - *Cold accelerometer*
    - *SQUID array sensor development*
    - *Magnetic imaging*
    - *Inertia measurement technology.*
  - ***Quantum Fluid Based Sensor and Modeling Technology***
    - *Gyroscope*
    - *Particle detectors*
  - *Four innovative technology development approaches have been preliminarily selected from these four sub-areas:*
    - *A Compact Atomic Laser using Micro-magnetic Trap Technology*
    - *Microcavity Sensors for Chemical/Biochemical And Biomedical Applications*
    - *Multiplexing SQUIDS for Brain Imaging*
    - *Superfluid Quantum Gyroscope (SQG)*

- ***Future - Space Quantum Sensors will evolve to be complete:***
  - *sensing physical parameters*
  - *processing data*
  - *making decisions*
  - *being self replicating*
  - *propagating themselves*
  - *forming networks*
  - *forming quantum networks*
- ***They will help man explore beyond the solar system***
- ***They will be man's robotic extensions to propagate space***
- ***We are looking forward to working with our international partners to achieve these goals.***

- The First International Symposium on Microgravity Research and Applications in Physical Sciences and Biotechnology was held September 9–15. 2000 in Sorrento, Italy.
- The meeting built on a successful series of symposia sponsored by the European Space Agency (ESA) in light of the international cooperation that has resulted in the assembly of the ISS.
- At this gathering, scientists from various nations presented recent results of theoretical, numerical, and experimental investigations in physical sciences and biotechnology, and their relevance to applications-oriented research, preparing the way for the release of a Microgravity Research International Announcement of Opportunity, which the International Microgravity Strategic Planning Group issued in October 2000.
- The conference allowed researchers to obtain detailed information on the objectives and the opportunities of the announcement, and gave them the opportunity to discuss joint research programs with their colleagues.
- To further assist in this endeavor, poster sessions dedicated to the experiment hardware provided by the international partners for the ISS were also presented.
- A proposal to form an International Technology Working Group (ITWG) to begin international collaboration activities has been met with great enthusiasm by the Symposium organizers and participants.

INTERNATIONAL COLLABORATION

- We are planning to formally establish the International Technology Working Group, initially within the microgravity fundamental physics technology areas. We propose that members of the ITWG will:

  - (1) Participate in the Fundamental Physics Advisory Group (FPAG), International Microgravity Strategic Planning Group and topical group meetings, international science symposia, workshops, and conferences in order to understand, communicate and address new technology requirements.

  - (2) Create and maintain a web-page, available to the international microgravity research community, containing an inventory of all existing and being developed technologies as well as information on all other technology related activities.

  - (3) Organize technology sessions during FPAG meetings to capture technology requirements, establish priorities, and convey to FPAG the existing technology capabilities.

  - (4) Initiate development of the Fundamental Physics technology Roadmap

  - (5) Plan and coordinate individual collaborative efforts in technology development addressing top priority requirements also with regard to their return potential to the economy.

- In the longer term, we know that our civilization will need to find ingenious ways of using the resources of space and to expand into space. The continuing exploration and utilization of space will require new tools. It is the prime responsibility of the ITWG to ensure that these new tools will be always available to our international research community.

Conclusions

- We are in the midst of an exciting revolution in the ability to observe and manipulate material at the quantum level. Physics and technology for next hundred years will be dominated by the technological advances associated with this new revolution The next few decades are certain to lead to new insights into the world of quantum physics and to dramatic advances in technology
- International collaboration in both fundamental physics research and technology will not only leverage international resources and eliminate duplication of effort, but, most importantly, it will also speed up future breakthroughs, specifically, in the exciting areas of quantum physics and quantum technologies.